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Wheat germ thermal treatment in fluidised bed. Experimental study and mathematical modelling of the heat and mass transfer

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Abstract

Wheat germ is an abundant by-product of the milling industry, it has excellent nutritional qualities and high tocopherols content. The aim of this work was to study the kinetics of wheat germ drying in fluidised thin-layers by applying analytical solutions of the diffusion equation. Also, was determined the effective heat transfer coefficient by solving the macroscopic energy balance to contribute with the design and optimization of a thermal treatment for this product. Four air temperatures were studied in this work, 90-150°C. The heat transfer coefficients were estimated using experimental drying rates (7.87 to 16.55 $W/m^2 °C$). The effective diffusion coefficient for water was determined to vary from 3.22×10^{-11} to 2.38×10^{-10} m^2/s. The analytical solution for short times was not suitable for this high temperature process. Values of diffusion coefficient and activation energy (39.27 kJ/mol) were within the ranges expected for food drying at elevates temperatures.

Key words

Wheat germ; Fluidization; Mathematical modelling, Effective diffusion coefficient, Effective heat transfer coefficient.

Notation

A_v	Specific particle surface, m^{-1}
a_w	Water activity
C_p	Specific heat of wheat germ particle, J kg^{-1} (dry matter) °C $^{-1}$
D_{eff}	Effective diffusion coefficient of water in wheat germ, m^2 s^{-1}
D_∞	Preexponential factor in Arrhenius equation for water diffusivity, m^2 s^{-1}
E_a	Activation energy kJ mol^{-1}
h_t	Effective heat transfer coefficient, W m^{-2} °C^{-1}
L_0	Half part of particle thickness at initial moisture content, m
L_g	Heat of desorption of water in the particle, J kg^{-1}
L_w	Heat of vaporization of pure water, J kg^{-1}
M_w	Molar mass of water, kg kmol^{-1}
p_v	Vapor pressure of water in particles, Pa
p_s	Saturation vapor pressure of pure water, Pa
p_{va}	Partial pressure of vapor in air, Pa
p_{vs}	Vapor pressure of water in the particle surface, Pa
R	Universal gas constant, 8.314, kJ kmol^{-1} K^{-1}
S_y	Standard deviation of the estimate
t	Time, s
T	Particle temperature, °C
W	Wheat germ moisture content, kg water/ kg dry matter
W_{ad}	Dimensionless wheat germ moisture content

Greek symbols

π	Constant
ρ_p	Particle density, kg m^{-3}
ρ_s	Dry matter density of wheat germ, kg m^{-3}

Subscripts

0	Initial
e	Equilibrium
exp	Experimental value
K	Kelvin
l	Local
m	Average
s	Surface
sim	Simulated value

1 Introduction

Wheat germ is the name given to the embryo of the wheat seed, an important by-product of the wheat milling industry. The germ represents approximately 2-3 g/100g of the whole grain weight, and contains between 8-14g of oil per 100g of germ (Capitani et al., 2011). Germ is considered a natural source of highly concentrated nutrients such as proteins, lipids, sugars and minerals, as well natural antioxidants as tocopherols, B-group vitamins, carotenoids, flavonoids, phytosterols and policosanols.

Typical applications around the world are germ-enriched bread, snack foods, and supplements to breakfast cereals, as well as wheat germ oil, mostly used in food, medical and cosmetic industries. A high amount of wheat germ is produced annually as a by-product of wheat milling industry in Argentina. In 2016 about 5.8 million metric tonne (FAIM, 2017) of wheat were milled, leading to about 174,000 tonne of wheat germ. Most of the germ produced is currently utilised for animal fed, though its potential for human consumption is high (Ge et al., 2000), due to its remarkable nutritional characteristics.

Wheat germ degrades rapidly, because the mechanical treatment involved in wheat milling, causes the rupture of some cells and thus the spreading of the oil. Degradation is mainly produced by the action of oxidative and hydrolytic enzymes such as lipase and lipoxygenase on the unsaturated fatty acids chains included in the lipid molecules of wheat germ (Brandolini and Hidalgo, 2012; Niu et al., 2013).

In order to limit the wheat germ enzymatic activity and to extend its shelf life, several stabilization processes had been applied: extrusion (Gómez et al. 2011), microwaving (Xu et al., 2013), infrared radiation treatment (Gili et al. 2017), steaming

(Ferrara et al., 1991; Sudha et al., 2007), dehydration (Rothe, 1963) as well as chemical preservation for instance by adding antioxidants (Barnes, 1948) or alkalis (Grandel, 1959).

Fluidization provides faster mass and, particularly, energy exchange between product and hot air, leading to a uniform treatment in the material being fluidised (Giner and Calvelo 1987) due to the high degree of mixing inherent to the process. Wheat germ flakes present good potential for fluidisation aimed at stabilising the product due to its non-sticky surface and low density (Gili et al., 2017b). Yöndem-Makascioğlu et al. 2005, studied wheat germ stabilisation employing a special type of fluidised bed, the spouted bed, and reported an increase of the shelf life in wheat germ by a factor of 20. Besides, a golden colour and a nutty flavour was imparted by light roasting.

However, to the best of our knowledge, no mathematical modelling for fluid bed drying of wheat germ has been proposed yet. The modelling and the parameters obtained from the energy and mass transfer allowed us to predict process behaviour, energy efficiency and optimize the thermal treatment for preservation of quality in the stabilized product. In addition, modelling and simulation are important for equipment design and may help industrial scaling up (Di Scala and Crapiste, 2008).

The dehydration stage can be studied by dividing the process conceptually into simpler systems. Thin layer drying involves the study of thin product layers under constant air conditions, thus all variations occur within the product and so, the drying parameter thus measured can be related to those air conditions (Márquez et al., 2006; Mohapatra and Rao, 2005).

The modelling of wheat germ thermal treatment by fluidised thin layer is the first step in the way to equipment design and then its industrial implementation. A rapid process is required to stabilise a material with high quality protein content, excellent fatty acid profile, high tocopherol, vitamin B and dietary fiber contents, which can be employed as a nutritionally-rich ingredient for foods, thus widening the range of products offered by the wheat milling industry.

On these grounds, the aim of this work was to study the mass and energy exchange of wheat germ in fluidised bed dryers by applying analytical solutions of the diffusion equation, solving the macroscopic energy balance and to compare the predictions with the experimental results.

2 Materials and methods

2.1 Materials

Wheat germ samples were provided by a local company (José Minetti y Cia. Ltda. S.A.C.I, Córdoba, Argentina) after grain milling (2015 harvest).

2.2 Preliminary operations

A sieving stage was utilized to separate the bran and flour fraction from wheat germ particles (EJR 2000, Zonytest®). Once the wheat germ particles were separated (93.3% in mass retained on 20 mesh-size (0.841 mm)), they were stored at –18°C in a three-layer package (polyester, aluminium and polyethylene) with barriers against oxygen and light until further use. The frozen storage process of wheat germ particles produces a negligible effect on its physical properties. In a previous study, the dimensions of wheat germ particles where determined: they had a flat ellipsoidal shape, an effective diameter of particle of 0.623±7.45 x10^{-8} mm, a major axis of 2.28±0.31 mm, a minor axis of 1.59±0.24 mm. The thickness was 0.29±0.03 mm (Gili et al., 2017b).

2.3 Moisture content

Moisture content was analysed according to standard method of American Association of Cereal Chemists (2012).

2.4 Fluidised bed equipment

The equipment used was a purpose-built fluidised-bed dryer, built in the workshop of the Faculty of Engineering, National University of La Plata, Argentina (Torrez Irigoyen and Giner, 2011). It is composed of (i) a thermally insulated drying chamber, 0.10 m internal diameter and 0.30 m in height with a double glazing inspection window made of borosilicate glass, (ii) a Testo 435 hot wire anemometer to measure air velocity upstream the chamber in cold airflow through a duct 1 m in length (0- 20 m/s, with an error of 0.03 m/s), (iii) a Testo 525 micromanometer (0–25 hPa, with an error of 0.2% at full scale) to measure pressure differences through the bed, (iv) an electronic temperature controller which include a software developed in Java language that allows the temperature of the air entering the chamber to be set (inlet air temperature), (v) a centrifugal fan, powered with a Siemens 0.55 kW electric motor (maximum angular speed, 2800 RPM), (vi) a WEG (Model CFW-08, Brazil) variable-frequency drive to control the air velocity by regulating the angular fan speed, and

(vii) two U-shaped nickel-plated copper resistance, 8 mm in diameter each, forms the resistor bank, capable to heat the air up to 325 °C.

2.5 Thin-layer drying in fluidised bed

The wheat germ minimum fluidisation velocity was previously determined (0.35±0.02 m/s) (Gili et al., 2017b).The drying process was performed with inlet air temperature of 90°C, 110°C, 130°C and 150°C using an average air velocity of 0.50±0.05 m/s, approximately 1.5 minimum fluidisation velocity, was used in order to have realistic results because this value is the operational velocity employed in thick fluidized beds. The wheat germ samples were spread on the drying chamber in a thin layer (0.03 m). The bed thickness did not alter the thin layer essence of the system because the air velocity is about ten times as high as in fixed bed drying.(Torrez Irigoyen and Giner, 2014).

Samples were treated at several times between 0.5 and 15 min in duplicate. After each period, samples were placed in sealed packages and stored under refrigeration. Temperature measurements were taken during treatment with an infrared thermometer Testo 832 T2 (Testo AG, Germany) being each experimental value the average of three readings.

3 Mathematical modelling of thin layer drying

3.1 Microscopic mass balance with diffusional transport of water

Assuming water transport by molecular diffusion and considering the wheat germ flake volume as a system, the microscopic mass balance can be expressed, for constant volume of wheat germ, as: (Crank, 1975)

$$\frac{\partial W_i}{\partial t} = \nabla\left(D_{eff}\nabla W_i\right) \qquad \text{Eq. (1)}$$

where D_{eff} is the effective diffusion coefficient of water relative to the dry matter.

As to the wheat germ particle had a flat ellipsoidal shape, a unidimensional water flux in slab geometry and constant diffusion coefficient, i.e. independent of moisture content was considered in agreement with Ruhanian and Movagharnejad (2016), Eq. (1) can be mathematically developed to give:

$$\frac{\partial W_l}{\partial t} = D_{eff}\left(\frac{\partial^2 W_l}{\partial l^2}\right) \qquad \text{Eq (2)}$$

This equation applies in each internal point of the solid, and provides the local moisture content of the diffusing component W_l as a function of the time t and the linear coordinate l, normal to the surface and, whose origin is placed at the centre of the slab.

3.2 Initial and boundary conditions in mass transfer

To solve the partial differential equation Eq. (2), the initial and boundary conditions were the following:

3.2.1 Initial condition

$$t = 0 \qquad W_l = W_0 \qquad 0 \leq l \leq L_0 \qquad \text{Eq (3)}$$

where L_0 is the half thickness of the wheat germ particle ($2L_0$) corresponding to the initial moisture content W_0.

3.2.2 Boundary condition at the centre

At the centre of the slab, the water flux is zero by symmetry

$$l = 0 \qquad \frac{\partial W_l}{\partial l} = 0 \qquad t > 0 \qquad \text{Eq. (4)}$$

3.2.3 Boundary conditions at the surface

At the surface, the convective outflow through the surrounding boundary layers to the hot air is equal to the diffusive water flux from the inside of the particle to the surface

$$-\rho_{s0} D_{eff} \frac{\partial W_l}{\partial l} = k_p (p_{vs} - p_{va}) \qquad \text{Eq. (5)}$$

A progressive decrease of p_{vs} towards p_{va}, or, in equivalent terms, a gradual decrease of the surface moisture content (W_s) towards the equilibrium value (W_e), calculated by sorption isotherm at the temperature and relative humidity of the drying air (Giner and Mascheroni, 2001), was postulated in the general surface condition presented by Eq. (5).

When the internal control of mass transfer is dominant, large mass transfer Biot numbers (Bi_m) are expected and the general surface condition presented by Eq. (5) reduces to a prescribed value:

$$l = L_0 \qquad W_s = W_e \qquad t > 0 \qquad \text{Eq.(6)}$$

Where W_s is the particular value of W_l at the surface. Considering the high air velocities employed during wheat germ thermal treatment by fluidisation, the external resistance may be considered negligible compared to the internal, thus implying a strict internal control for mass transfer. (Torrez Irigoyen and Giner 2014).

3.3 Analytical solution of the diffusion equation

The initial condition given by Eq. (3) and boundary conditions of Eq. (4) and (6), with the unsteady state diffusion model for plane sheet (Eq. (2)),can be analytically solved after integration in the solid volume to provide the mean moisture content W_m as a function of time (Crapiste and Rotstein 1997; Doymaz and Osman 2010; Vega-gálvez et al. 2011).

$$W_{ad} = \frac{W_m - W_e}{W_0 - W_e} = \frac{8}{\pi^2} \sum_{n=0}^{n=\infty} \frac{1}{(2n+1)^2} \exp\left[-\frac{(2n+1)^2 \pi^2}{4} \left(\frac{D_{eff} t}{L_0^2}\right)\right] \quad \text{Eq. (7)}$$

where W_{ad} is the dimensionless moisture content, or moisture ratio (Ah-Hen et al., 2013; Akpinar and Bicer, 2005). The group $D_{eff}\,t / L_0^2$ is the dimensionless time or Fourier number for mass transfer (Fo).

Becker (1959) has defined the dimensionless time as $X^2 = A_v^2 D_{eff} t$ being A_v the surface area per unit volume or $1/L_0$ for an slab geometry. So, replacing $D_{eff}\,t / L_0^2$ in Eq. (7) in term of as X^2 yields

$$W_{ad} = \frac{W_m - W_e}{W_0 - W_e} = \frac{8}{\pi^2} \sum_{n=0}^{n=\infty} \frac{1}{(2n+1)^2} \exp\left[-\frac{(2n+1)^2}{4} \pi^2 X^2\right] \quad \text{Eq. (8)}$$

To obtain the solution with the infinite series. a considerable number of terms is required to converge, particularly at short times. However, for long times, only one term of the infinite series suffices for convergence ($W_{ad} < 0.3$ or $X > 1$).

3.4 Approximate analytical solution of the diffusion equation

A simpler solution (Eq. (9)) of the diffusion equation proposed by Becker (1959) was used to estimate the drying curve at short dimensionless times ($X \leq 1$) without losing the accuracy of the full series solution (Eq. (8)) for the slab. The expression is:

$$W_{ad} = \frac{W_m - W_e}{W_0 - W_e} = 1 - \frac{2}{\sqrt{\pi}} A_v \sqrt{D_{eff}\, t} \qquad \text{Eq. (9)}$$

This type of solution was successfully applied for spherical geometry in other drying studies to predict grain drying curves.(M. C. Gely and Giner 2007; R. M. Torrez Irigoyen and Giner 2014). In the present study, this mathematical expression (Eq. (9)) was fitted to experimental data considering the half thickness of the particle at the initial moisture content (L_0).

The root mean square error of the estimate was calculated as:

$$S_y = \sqrt{\frac{\sum_{i=1}^{i=n} (y_{exp,i} - y_{pred,i})^2}{n-1}} \qquad \text{Eq. (10)}$$

Where $y_{exp,i}$ and $y_{pred,i}$ are the experimental and predicted values respectively, corresponding to the same treatment time.

3.5 Macroscopic energy balance

The wheat germ particle temperature is assumed to be uniform, i.e. the internal temperature profile in the particle is flat, although variable with time (Rodríguez-Fernández et al., 2007). This characteristic is due heat transfer Biot number, which tends to zero with the progress of drying (Giner et al., 2010). Therefore, a macroscopic energy balance was applied to the wheat germ particle, considering that the heat exchange between particle and air was regulated by an external control:

$$\rho_s C_p \frac{dT}{dt} = h_T A_v (T_a - T) - \rho_s \left(-\frac{dW_m}{dt}\right) L_g \qquad \text{Eq. (11)}$$

Where A_v is the specific particle surface (surface area/volume), T_a is the drying air temperature and $(-\,dW_m/dt)$ is the drying rate, based on the average moisture content, calculated from experimental data using a finite difference approximation.

The initial condition for the heat transfer equation obtained is $(\,t = 0)\ T = T_0$. In this ordinary differential equation, the derivatives are total since, as mentioned earlier, the temperature gradient within the product is assumed negligible while W_m is an average value spatially integrated in the particle (Rahman and Kumar, 2006; Torrez Irigoyen et al., 2014). It is important to highlight that the heat capacity (C_p) of wheat germ particle is based on the product dry mass (J/ kg dry matter °C), though it is nonetheless a function of the average moisture content of the particle.

The specific heat of particle was calculated from (Mohsenin, 1980) (Eq. (11)), for moisture content up to 0.7 kg water/kg dry matter.

$$C_p = 1638.08 + 3566.19\, W_m \qquad \text{Eq. (12)}$$

The energy balance was solved by utilizing the specific heat, calculated at every moment of the treatment, employing the average moisture content of the particle.(Torrez Irigoyen et al., 2014)

3.5.1 Heat of desorption

The enthalpy or heat of water desorption of wheat germ particle can be estimated with an expression deduced from the Clapeyron equation and a model for the sorption isotherm (Chen, 2006; Chenlo et al., 2011; Giner and Gely, 2005):

$$L_g = \frac{RT_k^2}{M_w}\left[\frac{d(Ln(p_s))}{dT_k} + \left(\frac{\partial(Ln(a_w))}{\partial T_k}\right)_w\right] \quad \text{Eq. (13)}$$

By operating mathematically on the right hand side of the equal sign in Eq. (13), we can find

$$L_g = L_w + \frac{R_g T_k^2}{M_w}\left(\frac{\partial(Ln(a_w))}{\partial T_k}\right)_w \quad \text{Eq. (14)}$$

Where the first term of the right hand side of the equal sign is the heat of vaporization of water, while the factor $(\partial Ln(a_w)/\partial T_k)_w$ is calculated using a sorption isotherm equation The heat of desorption was taken as equal to L_w, following the criterion adopted by R. M. Torrez Irigoyen et al., (2014) for soybeans.

3.5.2 Determination of the effective heat transfer coefficient during the thermal treatment of wheat germ by fluidisation

The macroscopic energy balance (Eq. (11)) is an ordinary differential equation solved by the Euler method using short times steps (T) were compared with the experimental thermal histories and, the residuals transferred to an optimization procedure of determination of h_t by minimization the sum of residuals squared (Eq.(15)).(Torrez Irigoyen et al., 2014)

$$SSR = \sum_{i=1}^{N} (T_{exp,i} - T_i)^2 \qquad \text{Eq. (15)}$$

Predictions errors were determined from the results of the fitting procedure by employing the absolute average deviation (AAD) (Eq. 16). Hence, errors were obtained in the same units as the dependent variable. The corrected coefficient of determination (r^2) was also calculated as an index of goodness of fit (Torrez Irigoyen et al., 2014).

$$AAD = \frac{1}{n} \sum_{i=1}^{n} \left| y_{exp,i} - y_{sim,i} \right| \qquad \text{Eq. (16)}$$

Where $y_{exp,i}$ and $y_{sim,i}$ are the experimental and simulated values.

4 Results and discussion

4.1 Experimental thin-layer drying curves in fluidised bed

The thermal treatment of wheat germ was carried out in a dryer at 90°C, 110°C, 130°C and 150°C using an average air velocity of 0.50 m/s. The experimental thin-layer curves can be observed in Fig. 1 where the measured dimensionless moisture content (W_{ad}) was plotted as a function of time.

W_{ad} was calculated as indicated in the left term of Eq. (7) where W_0 is the initial moisture content of the particle, W_m is the mean moisture content of wheat germ particle at time t, and W_e is the equilibrium moisture content measured in an extra-long treatment $(t > 3600\, s)$ carried out for each air temperature to consider the different relative humidity values at the various air temperatures used

An abrupt decrease of W_{ad} with time was found (Fig. 1). As expected, higher air temperatures led to higher absolute drying rates. The nonlinear behaviour of the curve and the fast evaporation of water from the surface of the particle indicated that wheat germ drying can be taken to occur during the falling drying rate period.

4.2 Approximate analytical solution of the diffusion equation

The Becker model (Eq. (9)), as mentioned before, is applicable to estimate the thin-layer drying curve in the range of $0.3 < W_{ad} < 1$ without losing the infinite series accuracy. This model was fitted to the experimental data of Fig. 1 by using a nonlinear least squares method (Systat, 1990). The parameters thus obtained and the statistical indexes of goodness of fit are presented in Table 1, while the predicted drying curves are depicted in Fig. 2.

As Fig. 2 shows, the short times equation (Eq. (9)) kept a good agreement with experimental data up to values of Wad of 0.2-0.3 despite the elevated air temperatures utilized during the treatments. The model was outside its applicability range for $W_{ad} < 0.3$ and the calculated values did not provide a good representation of observed values and, moreover, predicted negative values of dimensionless moisture content, which is physically absurd.

Based on the results obtained, the Becker model was inadequate to predict the entire thermal treatment of wheat germ particles in fluidised bed as a thin layer-drying equation for the thermal treatment applied to wheat germ particles. Due to the high inlet air temperatures utilized, at 150°C only a few points were correctly predicted by the Becker model. Comparable results were informed by R. M. Torrez Irigoyen and Giner (2014) for drying-toasting of presoaked soybean.

4.3 Analytical solution of the diffusion equation

In view of on the unsuitable fitting presented by the approximate analytical solution (Eq. (9)) for the all experimental data obtained at the several air temperatures, the complete analytical solution of the diffusion equation (Eq. (7)) was finally applied to predict the behaviour of the thermal treatment. The convergent infinite series (Eq. (7)) was fitted to the experimental data (Systat, 1990) by nonlinear square method. Eleven terms from n=0 until n=10 of the analytical solution were used in the fitting, which ensures practical convergence at all times. This criterion was maintained in all thermal treatments.

Fig. 3 shows the experimental dimensionless moisture contents and predicted values by Eq. (7) as a function of time over the four thermal treatments. The complete analytical solution described the sets of experimental data satisfactorily at each air temperature, and the diffusion coefficients obtained were similar to those reported in vegetables, seeds and grains (Gely and Santalla, 2007; Torrez Irigoyen and Giner, 2014; Vega-gálvez et al., 2011).

The accurate predictions of dimensionless moisture content were obtained in spite of the assumptions made of constant diffusion coefficient and constant particle volume, which are required for developing complete analytical solution (Crank, 1975). Although such premises for the analytical solution were not strictly realistic, the good prediction given by the model may be explained by the ratio ${D_{eff}}/{L_0^2}$ which keeps substantially constant in the equation.(Torrez Irigoyen and Giner, 2014).The results obtained from the fitting procedure and the statistical parameters of goodness of fit are shown in Table 2. Water diffusivity values determined here are comparable to 3.7x 10^{-12}- 2.32x10^{-11} (m^2/s) for air drying of quinoa at 60°C-90°C (Gely and Santalla, 2007), 7.76x10^{-10} – 9.35x10^{-9} (m^2/s) for carrots for air drying of carrot cubes at 50°C-70°C (Doymaz, 2004), 8.21 x 10^{-10} – 2.61x10^{-9} (m^2/s) for fluidised bed drying of castor oil seed at 90 °C and 110°C (Perea-Flores et al., 2012), and 1.39x10^{-11} – 3.94x10^{-11} (m^2/s) for spouted fluidised bed drying of barley at 36°C-56°C (Markowski et al., 2010). These values are consistent with the wheat germ diffusion coefficients estimated in the present work.

4.4 Dependence of diffusion coefficient with temperature

The dependence of the effective diffusion coefficient with temperature was studied for several authors in food drying (Gely and Giner, 2007; Guiné et al., 2012; Perea-Flores et al., 2012). An increase in the temperature speeds up molecular diffusion, and this effect is represented by a rise of the diffusion coefficient. A relationship with the inlet air temperature of the fluidised bed dryer can be described by an Arrhenius-type equation as follows:

$$Ln\left(D_{eff}\right) = Ln(D_{\infty}) - \frac{E_a}{R(T_a+273.15)} \qquad \text{Eq. (17)}$$

Where D_{∞} (m^2/s) is factor equivalent to the diffusivity at infinitely high temperature, E_a (J/mol) is the activation energy, a measure of the effect of temperature on the diffusion coefficient (related with the binding energy of between water and material) and R (8.314 x10^{-3} kJ/mol K) is the universal gas constant.(Perea-Flores et al., 2012).

An Arrhenius-type equation (Eq. (17)) was fitted to the diffusivities for each air temperature in order to determine E_a and D_{∞}. The predictions for the data obtained from the complete analytical solution (Eq. (7)) were showed in Table 2.

The activation energy (39.27 kJ/mol) was comparable to values reported by other researchers who studied diverse conditions of food drying (Guiné et al., 2012; Perea-Flores et al., 2012; Torrez Irigoyen and Giner, 2014; Zielinska and Markowski, 2007).

4.5 Determination of the effective heat transfer coefficient

The effective heat transfer coefficient was determined from macroscopic balance of energy (Eq. (11)). To solve the Eq. (11) the $C_p$and L_g were estimated according to Eq. (12) and (15). The wheat germ particle density (ρ_p) value utilized was 1234.23 kg/m^3 (Kim et al., 2003). The estimated heat transfer coefficients ranged between 7.87 and 16.55 W/m^2°C (Table 3). These results were lower than the coefficients determined by R. M. Torrez Irigoyen et al. (2014) during drying-toasting of presoaked soybean but were in the same range that values found for carrots by Zielinska and Markowski (2007).

The experimental and the predicted surface temperatures showed a reasonable agreement for all the air temperatures analysed (Fig. 4). Predicted curves somewhat overestimates the experimental temperature between 100 and 200 s. Particles were heated very fast; in fact, in a time shorter than 300 s the temperature of germ particles were close to the asymptotic or equilibrium air value. This abrupt approach of the particle temperature to the equilibrium temperature is explained by the intense heat exchange between air and particles that occurs during the fluidised bed process, due to the high degree of mixing experienced by particles inside the drying chamber. Furthermore, it is important to note that neither the shape of the experimental moisture curves (Fig. 1) nor the temperature heating profile of wheat germ particles (Fig. 4) denotes the presence of a constant drying rate period which indicates that the internal control considered in the model was appropriate.

5 Conclusion

In the present work, a thin layer mathematical model of heat and mass transfer for the thermal treatment of wheat germ, carried out at 90°C, 110°C, 130°C and 150°C, was applied to data in order to improve the understanding of this process that stabilizes germ particles as an ingredient for human consumption.

The moisture loss was observed to occur in the falling drying rate period. A strict internal control to the mass transfer rate, constant diffusion coefficient and constant particle volume was assumed to apply analytical solutions for unsteady state diffusion in a slab

The approximate analytical solution for short times or Becker model was unsuitable to describe the complete drying process at the high air temperatures used . On the other hand, the complete analytical series solution of the diffusion equation was able to describe with reasonable accuracy the experimental data of drying for all air temperatures

The experimental diffusion coefficients determined in this study were within the range expected for water diffusion in solids despite at the high temperatures used. Their dependence with air temperature was described by an Arrhenius-type equation. The activation energy (about 39 kJ/mol) was within the range expected for the drying of solid foods.

A macroscopic energy balance was solved to predict the transient temperature curve. By fitting the results of the numerical solution of this equation to the experimental data, the effective heat transfer coefficients were determined to each temperature analysed.

Both predicted dimensionless moisture contents and surface temperature of wheat germ as a function of time were in good agreement with the meas experimental measures.

The outcome of this study may be would be utilized in future work to relate thermal treatment, drying curve and the protective effect on nutritional quality for wheat germ particles both for human consumption or as raw material for the cosmetic industry.

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Table 1. Diffusion coefficients resulting from fitting Eq. (9) to experimental data of Fig. (1) ($W_{ad} \geq 0.3$) and their associated errors, the coefficient of determination (r^2) and root mean square error of the estimate (S_y).

Air Temperature (°C)	D_{eff} x 10 ^{10} (m^2/s)	r^2	S_y
90	1.1291	0.903	0.2352
110	1.7211	0.982	0.0924
130	2.2861	0.969	0.0908
150	7.5756	0.971	0.1233

Table 2. Diffusion coefficients resulting from fitting Eq. (7) to experimental data of Fig. (1) and their associated errors, the coefficient of determination (r^2) and root mean square error of the estimate (S_y). Also, the table shows the activation energy and the preexponential factor of the adjusted Arrhenius-type equation.

Air Temperature (°C)	D_{eff} x 10^{10} (m^2/s)	r^2	S_y	E_a (kJ/mol)	D_∞x 10^5 (m^2/s)
90	0.3220	0.942	0.2361	39.27	1.144
110	0.4438	0.985	0.1288		
130	0.5865	0.963	0.1127		
150	2.3768	0.990	0.0479		

Table 3. Heat transfer coefficients resulting from fitting Eq. (11) to experimental data and their absolute average deviation(AAD), the root mean square error of the estimate (S_y) and the coefficient of determination (r^2).

Air Temperature (°C)	h_t (W/m^2°C)	r^2	AAD (°C)	S_y
90	9.3192	0.824	4.6042	7.2102
110	9.4586	0.833	5.9767	11.3458
130	7.8747	0.896	6.0352	10.7551
150	16.5455	0.937	4.9280	11.5952

Figure 1. Experimental thin-layer curves during the drying-stabilization process of wheat germ particles at the temperatures of 90°C(●), 110°C(◇), 130°C (▲) and 150°C(□).

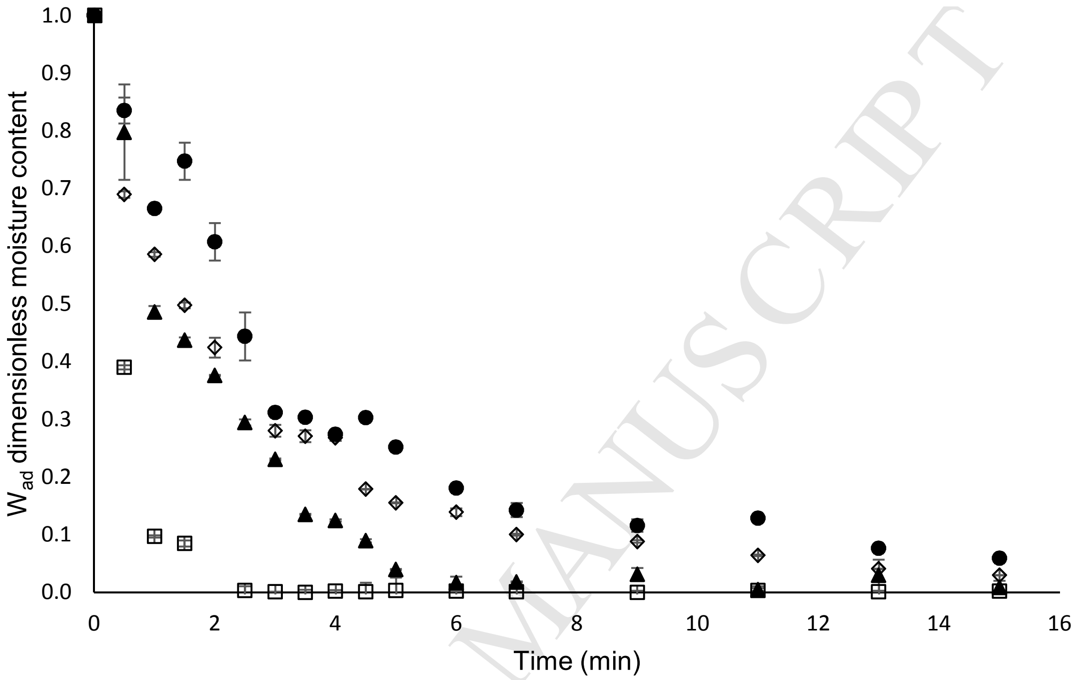


Figure 2. Thin-layer drying-stabilizing curves of wheat germ particle. Experimental data (●), and predicted values (-) by approximate analytical solution (Eq. (9)) for the inlet air temperature: (a) 90°C, (b) 110°C, (c) 130°C and (d) 150°C.

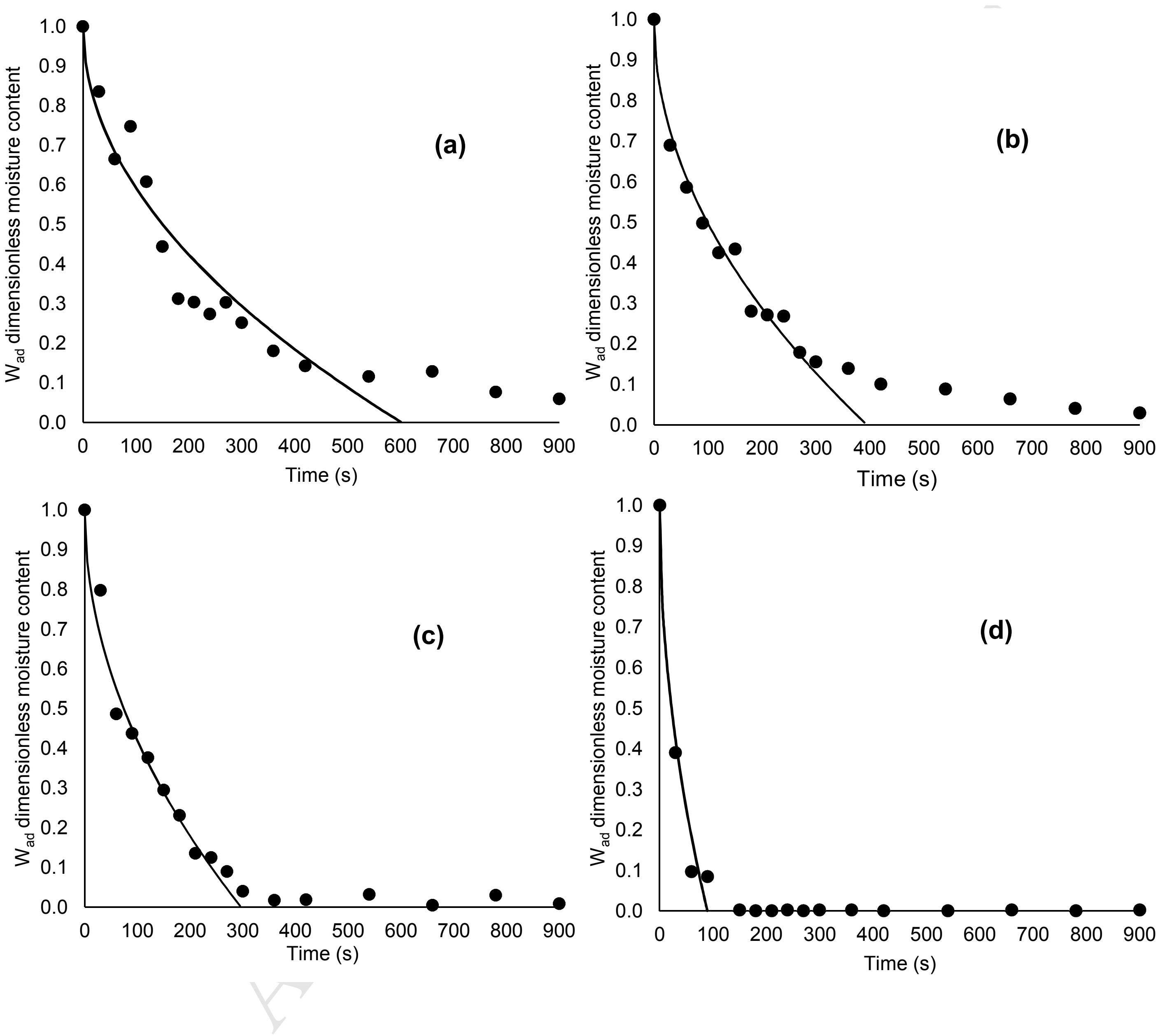


Figure 3. Thin-layer drying-stabilizing curves of wheat germ particle. Experimental data (●), and predicted values (-) by analytical solution (Eq. (7)) for the inlet air temperature: (a) 90°C, (b) 110°C, (c) 130°C and (d) 150°C.

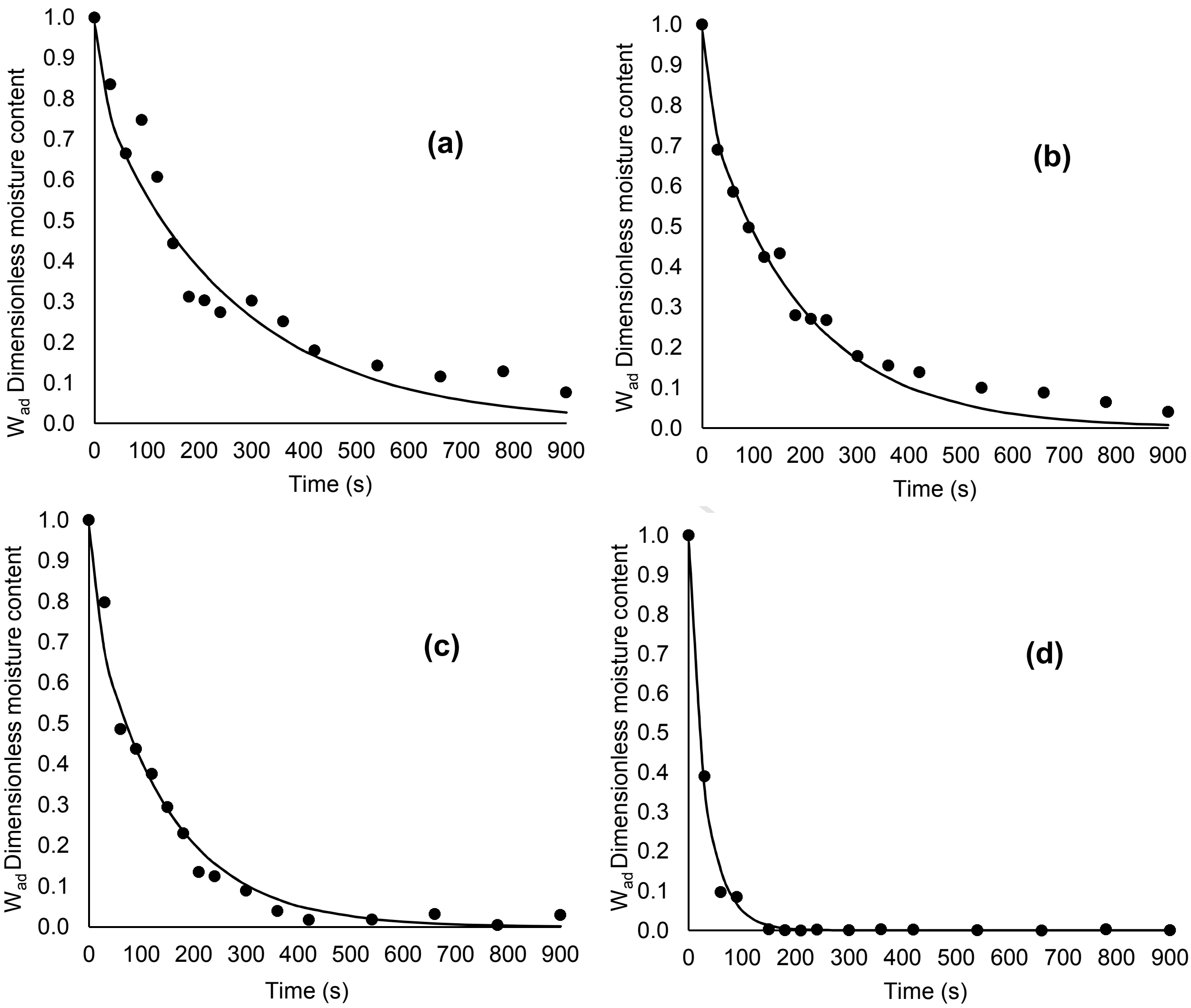
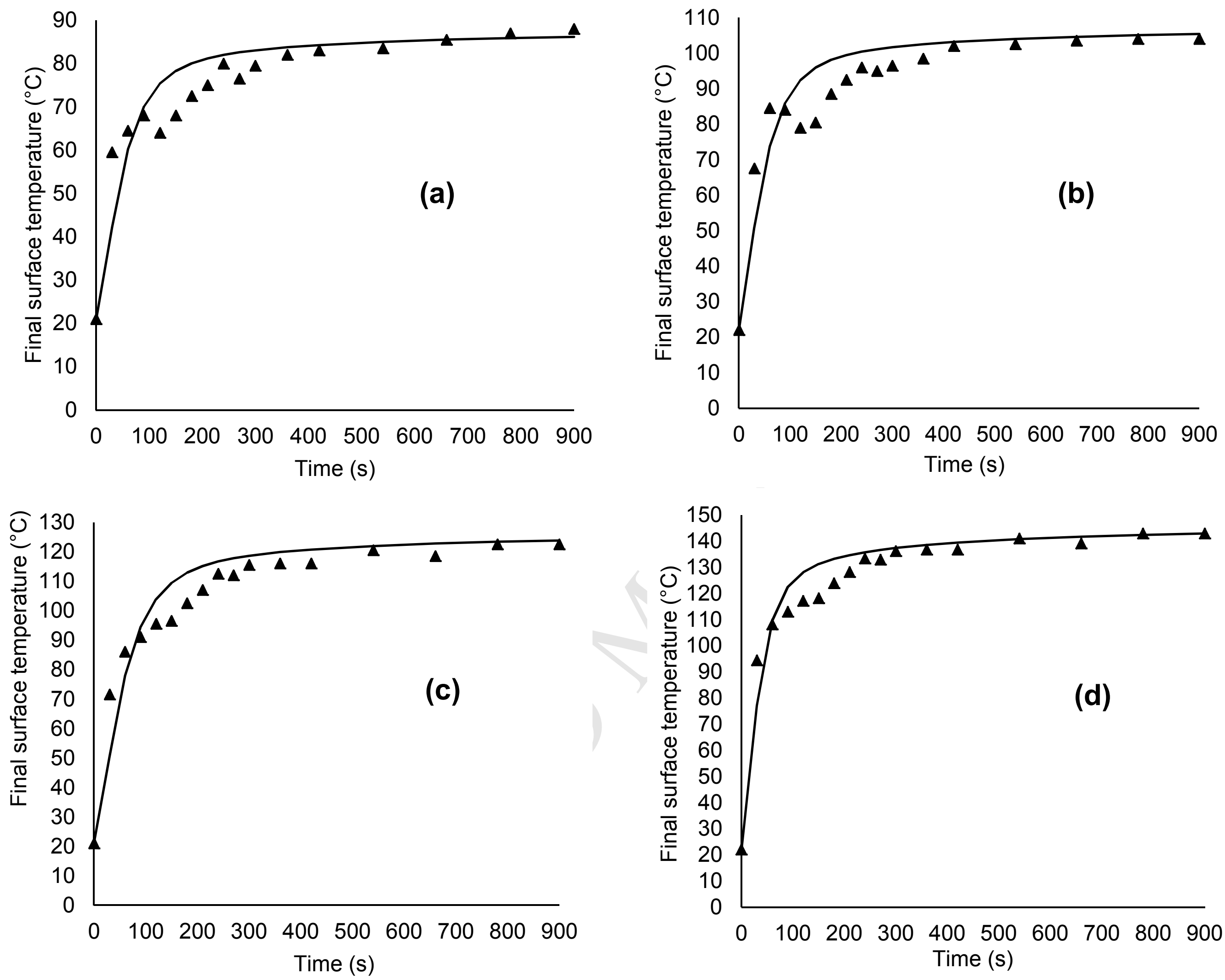


Figure 4. Wheat germ surface temperature curves as a function of drying-stabilizing time. Experimental data (▲), and predicted values (-) for the inlet air temperatures of: (a) 90°C, (b) 110°C, (c) 130°C and (d) 150°C.



Highlights

Fluidised bed drying of wheat germ particles at 90-150°C was studied.

Two analytical solutions with constant diffusivity and constant volume were tested.

The solution for short dimensionless times was not suitable in this process.

The complete analytical solution, a series, provided excellent agreement with data.

Heat transfer coefficient and Arrhenius parameters were estimated solving inverse problems.